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Biomechanical comparison of ex vivo lumbar vertebral fracture luxations stabilized with tension band or polymethylmethacrylate in cats

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Abstract: Objective: To evaluate spinal stabilization with tension band stabilization (TS) in cats compared to screw and polymethylmethacrylate fixation (SP). Study design: Ex vivo study. Sample population: Sixteen feline thoracolumbar spinal specimens. Methods: The intact specimens were mounted in a six-degree-of-freedom biaxial testing machine for nondestructive testing to obtain the neutral zones (NZ) and range of motion (ROM) in flexion and extension. Thereafter, nondestructive testing was consecutively performed after destabilization by disc fenestration and partial L1 corpectomy and after treatment with either TS or SP. Load to failure was compared after surgical treatment in flexion. Significance was assessed by Student's t test or Wilcoxon signed-rank test. Results: Range of motion was 26.4° ± 2.2° in TS constructs and 13.4° ± 2.1° in SP constructs (P = .0005). When flexion and extension were analyzed separately, no difference was found for ROM in flexion (SP, 7.0° ± 3.7°; TS, 8.3° ± 2.1°; P = .38). In extension, the mean displacement was 6.4° ± 2.7° and 18.1° ± 5.1° in SP and TS constructs, respectively (P = .0001). Neutral zone was 2.9° ± 0.6° and 7.5° ± 0.8° for the SP and TS groups, respectively (P = .0003). Screw and polymethylmethacrylate fixation constructs were two times stiffer (P = .045). Conclusion: Tension band stabilization provided stability comparable to SP in flexion. In extension, ROM of SP constructs was half that of TS constructs. The mode of failure of TS was related to the limited dorsal bone stock of feline lumbar vertebrae. Clinical significance: Surgeons should be aware of the limited stability in extension provided by TS when it is used to stabilize thoracolumbar spinal injuries. Our results provide evidence to justify additional studies to clarify the type of fractures amenable to TS.

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Article Title: Biomechanical comparison of ex vivo lumbar vertebral fracture luxations stabilized with tension band or polymethylmethacrylate in cats

Running Head: Feline spinal stabilization techniques—a biomechanical comparison

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Conflict of interest statement

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Abstract

Objectives: To evaluate spinal stabilization with tension band stabilization (TS) in cats, compared to screw and polymethylmethacrylate fixation (SP).

Study Design: Ex vivo study.

Sample Population: Sixteen feline thoracolumbar spinal specimens.

Methods: The intact specimens were mounted in a six-degree-of-freedom biaxial testing machine for nondestructive testing to obtain the neutral zones (NZ) and range of motion (ROM) in flexion and extension. Thereafter nondestructive testing was consecutively performed after destabilization by disc fenestration and partial L1 corpectomy and after treatment with either TS or SP. Load to failure was compared after surgical treatment in flexion. Significance was assessed by student t-test or Wilcoxon signed-rank test.

Results: ROM was 26.4°±2.2° in TS constructs and 13.4°±2.1° in SP constructs (*P*=0.0005). When flexion and extension were analyzed separately, no difference was found for ROM in flexion (SP, 7.0°±3.7°; TS, 8.3°±2.1°; *P*=0.38). In extension, the mean displacement was 6.4°±2.7° and 18.1°±5.1° in SP and TS constructs, respectively (*P*=0.0001). NZ was 2.9°±0.6° and 7.5°±0.8° for the SP and TS group (*P*=0.0003). SP constructs were two times stiffer (*P*=0.045).

Conclusion: TS provided comparable stability to SP in flexion. In extension, ROM of SP constructs was half of that of TS constructs. The mode of failure of TS was related to the limited dorsal bone stock of feline lumbar vertebrae.

Clinical Significance: Surgeons should be aware of the limited stability in extension provided by TS, when used to stabilize thoracolumbar spinal injuries. Our results justify further studies to clarify the type of fractures amenable to TS.

Introduction

Spinal fractures and luxations are frequent injuries in feline and canine trauma patients. Based on the scarce literature available, it can be assumed that about 16% (179/1283)[1] up to 26% (26/100)[2] of cats that are presented after a traumatic event are affected by vertebral injuries. In dogs the reported incidence rates are lower with 10% (24/235) of trauma patients having diagnosed vertebral fractures, excluding sacral fractures and luxations that affected additional 12% (28/235) of the dogs in this retrospective study.[3] In cats, spinal injuries are often a combination of vertebral fractures and luxations (65%; 23/49),[4] most commonly affecting the lumbar spine.[2,4-6] Nearly half of cats with spinal fractures and luxations (12/30) are euthanized within the first day after injury due to severe neurological deficits,[4] especially if the lumbar spine is affected.[2] Particularly for cats, but also for dogs, objective data regarding the necessity and indications for surgical over nonsurgical treatment is limited. Even less is known about the optimal surgical treatment techniques that can be used in the feline spine. The lack of comparative knowledge of spinal stabilization techniques leads to decision-making mainly based on expert opinion.[6,7]

The two more commonly utilized surgical treatment techniques for spinal fracture luxation in cats include tension band stabilization (TS)[5] and vertebral body stabilization by use of polymethylmethacrylate (PMMA) and pin or screw composite fixation (SP).[6] TS resulted in complete or satisfactory neurological function in 79% (30/38) of all treated cats and dogs, with none of the cats being affected by implant- or fixation-related complications.[5] In a smaller case series SP was applied as a uni- or bilateral construct in 8 cats, with 6 of those having an excellent to satisfactory outcome within a 12-month follow-up and only one experiencing an implant-related complication.[6] TS is preferred by some surgeons to treat spinal instabilities in cats because of its technical simplicity, low cost, and faster surgical time when compared to SP although a direct comparison of the techniques has never been performed in a clinical trial.

Using the spinous process as a point of fixation in TS is less invasive and may lower the risk of penetration of the spinal canal by screws or K-wires. However, the spinous processes are small and may not provide sufficient bone stock for implant fixation in cats potentially predisposing for implant failure. Even if TS may not counteract all acting forces in the feline spine, dorsal spinal stabilization may offer some biomechanical advantages as indicated in dogs.[8] Nonetheless, biomechanical data evaluating different spinal stabilization techniques regarding their stability and failure mode are missing. To investigate the biomechanical characteristics of commonly used surgical techniques in cats, we conducted a biomechanical study using an *ex vivo* flexion-extension model.

We hypothesized that (1) TS is comparable to SP in regards to range of motion (ROM) and neutral zone (NZ), (2) TS provides a similar stiffness and maximum load at defined failure, and (3) the mode of failure for TS will be implant pull-out due to limited dorsal bone stock.

Materials and methods

Study subject

Sixteen spinal specimens (10th thoracic vertebra to sixth lumbar vertebra) were harvested from cats older than 1 year of age. All cats were euthanized for medical reasons unrelated to this study. They were donated for research and teaching purposes by their owners, and written consent was obtained. The anatomic specimens were collected according to our institution's regulations. Medical history and radiographs taken of the alive patient were reviewed to exclude animals with spinal pathologies. Radiographic examination was not routinely performed in all specimen. Specimens with severe degenerative changes such as spondylosis, spondylarthrosis, and disc degeneration, or traumatic injuries of the spine, detected either on the taken radiographs or at the visual inspection during specimen preparation, were excluded from further analysis. Soft tissues were removed, leaving ligaments and facet joints intact. The specimens were wrapped in saline-soaked gauze and stored at –20°C for subsequent use. Prior to testing, specimens were thawed at room temperature for 24 hours. During the testing phase, the specimens were kept moist by regularly spraying them with saline and wrapping them in saline-soaked gauze. Spinal samples were randomly allocated to two treatment groups instrumented with either (1) screw and PMMA vertebral body stabilization (SP) or (2) tension band stabilization (TS). Sequential biomechanical tests were performed in each specimen for the following consecutive conditions: (1) intact/native (C1), (2) unstable, after incision of the L1-L2 intervertebral disc and removal of the L1 endplate (C2), and (3) stabilized (C3).

Surgical procedure

All interventions on the specimen were performed by a single surgeon (S.C.K.). TS was performed as previously described by Voss and Montavon (2004) with some minor modifications concerning the size of the implants[5] (Figure 1A). A 1.6-mm K-wire (DePuy Synthes, Oberdorf, Switzerland) was inserted in the base of the spinous process of L3 and bent to a U shape spanning the segments Th13 to L3. The free ends of the pin were secured with a 0.8-mm hemicerclage wire (DePuy Synthes, Oberdorf, Switzerland) through the spinous process of Th13 (Figure 1A). Thereafter, a 0.8-mm figure-of-eight wire was passed through the spinous processes of L1 and L2.

For SP three cortical stainless steel screws of 2-mm diameter and 2-cm length (DePuy Synthes, Oberdorf, Switzerland) were inserted in the L1 and L2 vertebral body (Figure 1B,C).[6] The insertion point of the screws was located at the level of the base of the transverse process. The trajectory used for drilling was along the transverse plane and dorsoventrally directed at an angle of approximately 10°, intersecting the center of the vertebral body and exiting through the opposite cortex.[6] During the insertion, 0.5 cm of the screw was left protruding off the bone to be embedded in PMMA. For consistency the dimension of the PMMA column applied around the screws was controlled after the application for its height, width, and length.

<u>Destabilization</u>

To create a L1-L2 vertebral instability the intervertebral disc was sharply incised with a scalpel blade and the cranial endplate was removed with a 2-mm wedge of the vertebral body using an oscillating saw. This instability model was based on a previously described model in dogs with modifications concerning the degree of instability created. Previous models either only incised the intervertebral disc or included a facet joint destabilization.[8-11]

<u>Biomechanical testing</u>

The length of the spinal segments tested differed for each treatment group. The surgical technique of TS requires fixation of four vertebrae while SP is applied only to 2 or 3 vertebrae depending on the fracture configuration (Figure 1). Therefore, in the TS group Th12 and L4 and in the SP group Th13 and L3 were potted in cylindric plastic tubes (52-mm diameter, 60-mm high) using PMMA. For reinforcement and stabilization of the adjacent segments, additional K-wires were inserted through the vertebral body and the facet joints (Th12 to Th13 and L3 to L4 for the TS group and Th13 to L1 and L2 to L3 for the SP group). Special care was taken so that movement of the segments of interest was not interfered with by the K-wires, leaving one (SP group: L1 - L2) and three (TS group: Th13-L1, L1-L2 and L2-L3) movable segments.

Prior to mounting the specimen to the testing machine, an alignment jig was used to correct the malalignment of each specimen after potting (Figure 2). This ensured consistency in specimen position during testing, as the fixture allowed only 10° of angulation for adjustments before testing. Biomechanical testing was performed using a custom-made six-degree-of-freedom spine testing machine mounted to a servohydraulic biaxial machine (INSTRON) (Instron Corp., Canton, MA, USA; Figure 3). One potted end was fixed to an arm attached directly to the Instron, allowing control of flexion/extension. The other arm was attached to the spinal testing machine, allowing the spine to translate freely on an XY-sliding table. This setup allowed the spine to flex with a pure moment about the center of the rotation, aligned at the L1-L2 intervertebral disc.

First, nondestructive testing was performed to obtain the NZs and the ROM.[8] The NZ was defined as the difference in angulation between the two phases of motion, flexion and extension at zero torque. ROM was measured as the peak-to-peak displacement difference between the minimum (-1N/m) and the maximum (1N/m) loads. The machine was programmed to perform six cycles using continuous loading at 0.25°/sec to 1 Nm in flexion and extension, the predominant motions in the thoracolumbar spine,[12-14] in each condition (intact, unstable, and stabilized). The first three cycles were performed to overcome viscoelastic creep of the specimen.[15] Cycles 4 to 6 were used to calculate the NZ and ROM.

Load to failure (LF) was then applied in flexion at a rate of 1°/sec and load-displacement curves were established. Two different outcome measures were documented for LF testing: stiffness at a defined displacement and the peak LF. The stiffness was calculated from the upward slope of the load-displacement curve. The peak LF was defined in the SP group as a sudden drop in the load-displacement curve. The average angle at which SP failed was used as the clinical failure value for comparison between the techniques. Thus, the peak LF for both techniques were calculated at the angle of failure of SP. Furthermore, mode of failure was recorded during and after testing by visual inspection.

Statistical analysis

Statistical analysis was performed using commercially available software (Graphpad Prism 7, La Jola, USA). For the continuous variables, data were presented as mean ± standard error of the mean. Body weight and PMMA block dimension are presented as median and range. Normal distribution of the data was assessed using the D`Agostino and Pearson omnibus normality test. Depending on data distribution, parametric unpaired Students' t-tests, or nonparametric tests, Wilcoxon rank sum test was used for inferential statistics. Hysteresis curves (moment-rotation angle) were used to define ROM and NZ for the direction of flexion and extension. The significance level was preset to $P < 0.05$ for all tests.

Results

Mean body weight in the two treatment groups did not differ, with 5.5 ± 1.6 kg for SP and 4.1 ± 0.75 kg for TS, respectively (*P* =0.150). PMMA block dimensions in the SP group for thickness, length, and width were 8.4 ± 0.3, 32.9 ± 3.4, and 14.4 ± 2.2 mm, respectively.

Total ROM and NZ with ± 1 Nm were higher (*P* = 0.0005 and *P* = 0.0003) in the TS group (26.4° ± 2.2° and 7.5° ± 0.8°) compared to the SP group (13.4°±2.1° and 2.9°±0.6°; Table 1). When flexion and extension were analyzed separately, no difference was found for ROM in flexion (SP, 7.0° ± 3.7°; TS, 8.3° ± 2.1°; *P* = 0.38). However, in extension, the mean displacement was 6.4° ± 2.7° and 18.1° ± 5.1° for the SP and TS group (*P* = 0.0001), respectively.

After both fixation techniques ROM in flexion was decreased (SP, *P* < 0.0001; TS, *P* =0.0001; Figure 4). The magnitude of reduction of ROM in flexion compared to extension was different in the TS group (*P* ≤ 0.0001) but not in the SP group (*P* = 0.69). ROM decreased by 387% in flexion and 582% in extension when comparing C1 and C3 in the SP group. In the TS group, ROM decreased 429% in flexion and 305% in extension after implant application compared to the intact condition (C3 vs C1).

Stiffness was greater in the SP group (0.14N/° ± 0.03N/°) compared to the TS group (0.07N/° ± 0.01N/°; *P* = 0.045; Figure 5). The load at failure in the SP group was 4.08N ± 1.86N with a failure angle of 25.9° ± 8.69°. In the TS group the load at this defined failure angle was 4.12N ± 0.90N, being not different compared to the SP group (*P* = 0.65).

For the TS group, the most common mode of failure was implant pull-out due to bone failure at the most cranial spinous process (Figure 6). The implant pulled out through the base of the spinous process of Th13 in 5 out of 8 specimens. In 2 specimens the failure occurred in the most caudal spinous process. In 1 case the U-shaped K-wire slipped out of the cerclage, and in

1 case implants sliced through the base of the spinous process of L5. For the SP group the modes of failure included breakage of the PMMA column over the defect (4/8), screw loosening (1/8), and bone failure (3/8). In the remaining 3 specimens the fixation of the spine within the PMMA blocks failed before implant failure occurred.

Discussion

This is the first study that performed a mechanical testing of the feline spine. In this biomechanical study comparing two spinal stabilization techniques in cats, we found that the SP reduced the total ROM and the NZ more than TS. During flexion the ROM of TS was similar to SP, but in extension it was higher for TS, leading us to reject our first hypothesis. We also found that the mean stiffness in flexion for TS was lower than for SP. In contrast, LF testing showed that the load at the defined failure angle in the TS group was not different from the load at failure in the SP group. Thus, our second hypothesis can only be partially accepted. The most common failure mode in TS was implant pull-out, indicating that the meagre dorsal bone stock is the limiting factor.

In our study we found that TS resists flexion better than extension, but SP performed well in both directions. In flexion TS reduced the ROM as much as SP, while in extension the reduction was 2 times higher in the SP group. These results are expected because in dorsal stabilization techniques the implants are applied on the tension side of the spine,[8] while in extension the implant is on the compression side, providing less resistance to the bending forces.

In the canine and human lumbar spine, flexion and to a lesser extent extension are considered to be the predominant motions during daily activities. Thus, surgical stabilization techniques should counteract the bending moments resulting from flexion and extension.[5,8-11,13,16-19] It can be assumed that in cats implant failure will occur in flexion as a similar motion pattern in dogs and people is likely. However, an accurate description of in vivo spinal kinematics in cats is not available. There is only one study that assessed the passive ROM of the spine in cats under anesthesia using radiographic measurements.[19] In this study during passive maximal flexion and extension, measured joint angle of the L1-L2 segment was up to 15° and an estimate of 60° for Th13 to L3.[19] We found slightly higher values in our study, with a ROM of 27° in L1-L2

(SP group) and 68° in Th13-L3 (TS group). These minor differences may be caused by the removal of soft tissue and the load of ±1 N/m that was applied in our study.

Based on our results we can conclude that SP is a stiffer fixation technique than TS. However, the clinical relevance of these data is unknown because TS and SP were not different in both nondestructive testing (restriction of flexural motion) and LF in flexion. The difference in stiffness between dorsal (TS) and ventral (SP) stabilization techniques differs from what was reported in dogs.[8] A canine cadaveric study demonstrated greater stiffness of dorsal laminar plating in comparison to vertebral body plating of L1-L2.[8] The results of this report may be more reliable than our study because the same bone plates were used for dorsal and ventral stabilization, supporting the biomechanical superiority of dorsal stabilization techniques. Even if TS has never been evaluated in dogs, the stiffness and strength of spinous process plating are not different from dorsolateral vertebral body plating and PMMA and pin vertebral body fixation.[9] A direct comparison of stiffness between our SP group and screw and PMMA fixation applied in other biomechanical studies in canine lumbar vertebrae shows that in our investigation SP is less stiff.[11,16] However, this is expected due to the greater amount of PMMA applied in dogs, the larger implant size used, and the greater bone stock of canine vertebrae.

In our study we simulated a fracture-luxation configuration resembling the most common type of spinal injuries in cats, namely, fracture luxations and wedge compression fractures of the vertebral body. The latter include endplate fractures affecting half of all presented patients.[4] The defect was created by complete incision of the L1-L2 intervertebral disc and a ventral wedge-shaped osteotomy of the caudal L1 vertebra. The dorsal compartment functioning as a tension band remained mainly intact despite the removal of the paraspinal muscles. A similar defect was created in Knell et al.'s study with an incision of the entire L1-L2 intervertebral disk.[8] Other biomechanical studies additionally destabilized the dorsal compartment of L3-L4 by articular facet joint removal and dorsal ligament transection. [9-11] In our experience TS is a reliable technique for endplate fractures, but it might not offer enough stability when all the vertebral compartments are involved. In these cases, a technique providing buttress fixation such as SP is indicated. Furthermore, we had to resect important soft tissue structures stabilizing the spine. Those may remain intact to a different extent using TS or SP, altering the clinical outcome of the techniques to a different extent. If bilateral SP constructs are used, in cats a dorsal approach to the spine is described[6] for adequate exposure and reduction of the fracture and visualization of the vertebral body. This approach is far more invasive compared to a dorsal approach to the spinous processes required for TS. However, a modified bilateral dorsolateral spinal approach can be performed for bilateral SP constructs, whereby the dorsal soft tissue stabilizers may remain intact.

The availability of sufficient dorsal bone stock is critical for the application of TS. Thus, the feasibility of TS is restricted regarding the anatomical localization and integrity of the dorsal compartment, namely, the base of the spinous process and the lamina. This clinical recommendation is supported by our results, as the most common failure of TS was implant pull-out at the cranial implant fixation site in Th13 (Figure 7). This finding contrasts with the paper that initially described the technique in clinical cases of dogs and cats as the figure-of-eight hemicerclage wire was suspected to be the weak point of the construct.[5] It must be considered that Voss and Montavon used the technique not only in feline patients, but also in canine patients. Implant-related failures of the construct were only experienced in dogs, and only in dogs weighing over 15 kg, in whom the TS technique is considered inappropriate for spinal stabilization.[5] Accordingly, our study gives new insights on the mode of failure in cats that were not reported so far.

All studies are not without limitations. As in most ex vivo investigation, cadaveric spines with removed muscular tissue were tested. Because in vivo contributors to spinal stability were missing, the load that must be withstood by any instrumentation construct is not equal to the acting loads in patients.[20] In vivo, the musculoskeletal apparatus is thought to play an important role in vertebral stability, although it is unclear whether the paravertebral muscles exert much stabilizing effect in paralyzed patients.[21] Therefore, our fracture model might show different degree of instability in an ex-vivo setup up. The effect of the surgical approach (either dorsal, lateral or modified dorsolateral) and the resulting different amount of soft tissue dissection have not been investigated in this study. Therefore, our results may under- or overestimate the performance of one technique over another if compared to the performance in vivo.

Another limitation of this study is that stability in lateral bending and rotation was not investigated as we assumed flexion to be the main motion of the thoracolumbar spine. Using flexion for the LF test and applying maximal and minimal loads of 1 N/m was built around this assumption. It is unclear how much reduction of ROM is necessary to achieve an appropriate spinal stability in cats, a common problem in biomechanical spinal testing. Because of the limited knowledge of the feline spine, this experimental setup was developed based on other similar studies in dogs.[8-11] Also, the effects of different angular deformation rates used from non-destructive test and LF test is unknown. It is assumed that the effect is relatively small and negligible, because the load rate is relatively slow and movement reduction post treatments are large. Other potential drawback is the different number of spinal segments used for comparison, due to different method of the two surgical techniques. As the main purpose of the spinal stabilization techniques is to eliminate motion between the segments post-surgical stabilization there should be no movable segments for both groups. The results from two surgical technique groups were achieved with this assumption. The difference in specimen length is considered and the moment is compensated during each testing with the custom-made six-degree-of-freedom spine testing machine that allows to flex the spine by applying a moment at the facture location.

We introduced a feline model to investigate the biomechanical characteristics of two different thoracolumbar spinal stabilization techniques. Our data can be used to increase knowledge of the biomechanical characteristics of the feline spine and spinal stabilization techniques. We conclude that both TS and SP provide comparable stability in flexion. However, in extension SP decreases ROM in comparison to TS by a factor of 2 and, similarly, stiffness is twice as high after application of SP in comparison to TS. Surgeons should be aware of the construct's limited stability in extension when using TS for stabilization of thoracolumbar spinal injuries. Further preclinical and clinical investigations including different fracture types are needed to conclude which technique is superior to the other. It needs to be assessed if the TS technique may be advantageous in less severe fracture-luxation types not involving the dorsal compartment, while SP should be chosen in highly unstable injures in which all compartments are involved.

Acknowledgments

Beer P., Mag. med. vet.

Beer P. was substantially involved in the design of the study and data acquisition during biomechanical testing. She was responsible for the specimen collection and preparation and assisted the surgical interventions. She was involved in the collection, analysis and interpretation. Beer P. drafted the manuscript, revised it and approved the submitted versions of the manuscript. She agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Knell S.C. was substantially involved in the design of the study and data acquisition during biomechanical testing. He performed all the surgical interventions. He was involved in data collection, interpretation and the statistical data analysis. Knell S.C. revised the manuscript drafts critically and approved the submitted versions of the manuscript. He agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Pozzi A. as experienced researcher in small animal orthopedics was substantially involved in the design of the study and provided essential scientific input. He was involved in the interpretation of the acquired data. Pozzi A. revised the manuscript drafts critically and approved the submitted versions of the manuscript. He agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Park B.H., PhD

Park B.H. was substantially involved in the design of the study and was the primarily responsible for the biomechanical test setup. He performed data collection, analysis, interpretation, including the statistical data analysis. Park B.H. revised the manuscript drafts critically and approved the submitted versions of the manuscript. He agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Disclosure

The authors declare no conflict of interest related to this report.

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Figure legend

Figure 1: Illustration of the tension band stabilization (TS) and the screw and PMMA (SP) technique for the vertebral stabilization of an L1-L2 defect (red triangle): (A) For TS a K-wire is inserted in the base of the spinous process of L3 and bent to a U shape spanning the segments Th13 to L3. The free ends of the K-wire are secured with a hemicerclage wire in the spinous process of Th13, and a figure-of-eight wire is passed through the spinous processes of L1 and L2. (B) Dorsal view on the SP technique: For SP three cortical screws were inserted in L1 and L2 vertebra with two screws entering the vertebral body on one side and one screw on the other side, avoiding interference with the screw(s) from the contralateral side. During the insertion, 0.5 cm of the screw and screw head was left protruding the bone to be embedded in PMMA (blue bar). (C) Transverse cut through the a stabilized L2 vertebra: The insertion point of the screws was located at the level of the base of the transverse process with an insertion trajectory approximately transverse and in a 10° angle to the sagittal plane, intersecting the center of the vertebral body and exiting in the opposite cortex.

Figure 2: Calibration frame for visual laser-guided specimen orientation in its anatomical sagittal and dorsal plane. The 6 degrees of freedom of the specimen clamping system allows independent rotation of the specimen for alignment in neutral position and correction of malalignment of each spine within the acrylic block after potting. The alignment plates are then fixed for the duration of all biomechanical tests.

Figure 3: Test setup for biomechanical testing. The specimen, here stabilized with tension band stabilization, is mounted with its two on-molded PMMA blocks onto the gripping end pieces of the 6-degree-of-freedom servohydraulic biaxial testing machine (Instron Corp., Canton, MA, USA). The arm to the right is rotating force controlled, allowing control of flexion/extension around the center of rotation at the intervertebral disc of L1-2. The arm on the left is attached to the spinal testing machine, mounted on a freely moving XY slide.

Figure 4: Hysteresis curves of the nondestructive testing in the intact (blue), unstable (red), and stabilized (green) conditions for the screw and PMMA fixation group (A) and the tension band stabilization group (B). ROM and NZ were higher (*P* = .0005 and *P* = .0003) in the TS group compared to the SP group, with no difference found for flexion (*P* = .38). ROM decreased between the intact and stabilized conditions in both groups (SP, *P* < .0001; TS, *P* = .0001) while NZ was not different (SP: *P* < .91; TS: *P* = .99). ROM in flexion was reduced to a greater extent than extension in both groups.

Figure 5: Bar graphs resembling the angular displacement in degree of specimen after surgical stabilization of the defect (condition 3) with either screw and PMMA vertebral body stabilization (SP) or tension band stabilization (TS) in (A) flexion and (B) extension, for the (C) ROM and (D) NZ. In extension angular displacement was higher in SP compared to TS *(P* = .0001) while ROM (*P* = .0005) and NZ *(P* = .0003) was higher for TS. € Stiffness (N/°) in LF testing in flexion was greater for SP compared to TS *(P = .045)*.

Figure 6: Specimen after LF testing in the screw and PMMA group (A) and tension band stabilization group (B). The most common mode of failure was breakage of the PMMA column over the defect in the SP group (A), specifically on the side where 2 screws were inserted and the PMMA block formed around. In the TS group pull-through of the cranial cerclage through the cranial spinous process (B) was seen most often.

Figure 7: Dorsoventral (A,C) and lateral (B,D) radiographs of the lumbar specimen instrumented by screw and PMMA fixation (SP) or tension band stabilization (TS) after LF testing. (A and B) Failure of SP occurred in the intervertebral space cranial to the stabilized L1-L2 segment (red arrow), showing that the PMMA construct was more stable than the immobilized Th13-L1 segment. (C and D) Failure of TS was pull-through of the cerclage through the cranial spinous process of Th13. The cerclage is free and is not anchored within the bone anymore.

Tables

Table 1: Biomechanical outcome measures for the tension band stabilization group for the intact (C1), unstable (C2), and stabilized (C3) conditions.*

* Range of motion (ROM) was measured as the peak-to-peak displacement difference between the minimum (-1 N/m) and the maximum (1 N/m) axial loads. Neutral zone (NZ) was defined as the difference in angulation between the two phases of motion, flexion and extension at zero torque. Stiffness was measured at a defined displacement from the upward slope of the load-displacement curve. Torque was the load to reach 100% ROM of the intact specimen to normalize for the different lengths of the specimen.

† Represents a difference compared to C1.

Variable	Condition	SP	TS
Flexion (°)	C1	12.52±1.7	23.64±3.2
	C2	20.82±2.4†	34.65±3.2*
	C3	6.97±1.2†	8.24±0.7*
Extension (°)	C1	-14.87±2.2	-44.14±5.3
	C2	-29.94±3.1†	-52.44±2
	C3	-6.36±0.9†	-18.1±1.7*
ROM (°)	C1	27.4±2.7	67.9±7
	C2	50.86±3.3†	87.4±3.9*
	C3	13.4±2.1†	26.4±2.2*
NZ (°)	C1	2.7±1.3	7.5±3.1
	C2	8.1±2.7†	9.2±2.9
	C3	2.9±0.6	7.50±0.8
Stiffness (Nm/°)	C3	0.14±0.03	0.07±0.01
Torque (Nm)	C3	1.8±0.26	3.3±0.38